

Durable High-Density Data Storage¹

Bruce C. Lamartine

Roger A. Stutz

Los Alamos National Laboratory

Mail Stop B229

Los Alamos NM 87545

rstutz@lanl.gov

505-665-5615

505-665-3456 fax

Abstract

Information technology has completely changed our concept of record keeping. The advent of digital records was a momentous discovery, as significant as the invention of the printing press, because it allowed huge amounts of information to be stored in a very small space and be examined quickly. However, digital documents are much more vulnerable to the passage of time than printed documents, because the media on which they are stored are easily affected by physical phenomena, such as magnetic fields, oxidation, material decay, and by various environmental factors that may erase the information. Even more important, digital information becomes obsolete, because, even if future generations may be able to read it, they may not necessarily be able to interpret it. This paper will discuss the Focus Ion Beam milling process, media life considerations, and methods of reading the micromilled data.

The Focus Ion Beam (FIB) micromilling process for data storage provides a new non-magnetic storage method for archiving large amounts of data. The process stores data on robust materials such as steel, silicon, and gold-coated silicon. The storage process was developed to provide a method to insure the long-term storage life of data. We estimate that the useful life of data written on silicon or gold-coated silicon to be on the order of a few thousand years without the need to rewrite the data every few years. The process uses an ion beam to carve material from the surface, much like stone cutters in ancient civilizations removed material from stone. The deeper the information is carved into the media, the longer the expected life of the information.

The process can record information in three formats: 1) binary at densities of 23Gbits/square inch, 2) alphanumeric at optical or non-optical density, and 3) graphical at optical and non-optical density. The formats can be mixed on the same media; and thus, it is possible to record, in a human-viewable format, instructions that can be read using an optical microscope. These instructions provide guidance on reading the remaining higher density information. The instructions could include information about the formats

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of the data, how to interpret the data bit-stream, and information on the types of readers or methods that can be used to recover the data.

There are several methods to read the information written with the ion beam. The selection the method is based on the density of the written data. Human-viewable data written at optical densities can be read with optical microscopes; binary data written at optical densities can be read much like currently CDs. Data written at non-optical densities can be read using force/tunneling microscopes or SEM readers. In any case the information read can be integrated with a computer.

Introduction

Information technology has completely changed our concept of record keeping. The advent of digital records was a momentous discovery, as significant as the invention of the printing press, because it allowed huge amounts of information to be stored in a very small space and be to examined quickly. However, digital documents are much more vulnerable to the passage of time than printed documents, because the media on which they are stored are easily affected by physical phenomena, such as magnetic fields, oxidation, material decay, and by various environmental factors that may erase the information. Even more important, digital information becomes obsolete, because, even if future generations may be able to read it, they may not necessarily be able to interpret it.

For data storage over hundreds to thousands of years, there is reasonable concern about effects of man-made or natural disasters. Fires and floods have destroyed many major data bases, for example, the great library at Alexandria, burned in about 642 AD. Exactly who was responsible is debated, but an irreplaceable storehouse of knowledge was almost totally destroyed. HD ROM (ion micromilling) technology discussed below would survive most such disasters. The melting point of stainless steel is approximately 2500 degrees F (1370 C) and can be used as the media for data storage with this process. Most building fires burn at about 1300 degrees F (700 C), thus the probability of data survival is quite high. It is noted that there are circumstances in which sustained fires can reach higher temperatures. Again, choice of materials for HD ROM storage can be designed to resist the most aggressive fires. However, simple placement of storage media in buildings that do not contain materials with high temperature combustibility would provide adequate protection. Of course, flooding is of little concern provided abrasion can be eliminated.

Comparisons with other technologies

With these concerns in mind, one can look for methods where information has been preserved for very long periods of time. A primary example is paper. Paper has been used for several thousands of years and has proved, on the whole, to be a reasonably stable media for the storage of information. Paper provides a means of storing

information in a native language format that can be understood by large numbers of people. The printing press expanded the role and dependence on paper as a means for storing information. Nevertheless, paper has limitations that reduce its usefulness as a long term medium. The Europeans are now beginning to see deterioration in 500-1000 year old documents produced on low acid paper. Many documents produced within the last hundred years on common paper (high acid content) are so deteriorated that they are even hard to micro-film.

Limitations of paper:

- Fire
- Mold
- Environmental reactivity
- Slow information search and read rates
- Fading of inks
- Media life of about 1000 years depending on storage conditions

Advantages of paper:

- Native language
- Easy to copy
- Does not require special equipment to read or write

The next example, from recent times, is the use of microfilm as a storage media. Microfilm provides a native language capability. It also provides a method of reducing the volume required to hold the information. Copies are easy and cheap to make but still harder than making copies of paper documents. Microfilm is accepted in courts and generally as a replacement for paper documents. It is relatively hard to tamper with the information that is copied to microfilm. However, microfilm generally has the same disadvantages as paper with the addition that it requires an enlargement device to read the information.

Limitations of micro film:

- Fire
- Mold
- Environmental reactivity
- Slow information search and read rates
- Loss of resolution
- Requires an enlargement device to read
- Requires chemicals for processing the film
- Media life of about 50 - 500 years depending on storage conditions

Advantages of microfilm:

- Reduced space requirements
- Hard to modify information
- Accepted by legal system
- Native language

The development of magnetic storage was next in the chain that provided a means to store ever increasing amounts of information on compact media. Magnetic storage can be divided into two main groups - tape and disk. Both can provide high data densities in the order of 1 Gbit per square inch. Magnetic technologies are reaching the limits for storing information. Furthermore, large improvements in areal density are not anticipated because of the minimum size of magnetic domains. The main advantages to magnetic media are the ability of machines to quickly read and write information, to store large amount of information, to update and append information depending on formats, and to correct some errors with built-in error correction information. However, there are a number of disadvantages to the digital storage of documents over printed documents. First, magnetic tape and disk media that are used to store digital documents are easily affected by physical phenomena, such as magnetic fields, oxidation, material decay, and by various environmental factors that may erase the information. Even more important, digital information becomes obsolete because, even if future generations may be able to read it, they may not necessarily be able to interpret it. This is the result of requiring a bit stream interpreter to convert the information from a sequence of one and zero to numbers and text. Another concern for the archivist is that information stored on magnetic medium can be changed without leaving any indications of a change.

Limitations of magnetic storage:

- Fire
- Local RF and EMP fields
- Environmental reactivity
- Overwrite capability (advantage in some applications)
- Magnetic fade
- Requirement for bit stream interpreters
- Medium life of about 2-10 years depending on storage conditions
- Not native language

Advantages of magnetic storage:

- Rapid reading and writing
- Relativity high data densities
- Error correct capabilities

Optical storage systems are a recent addition to storage methods. They provide a non-magnetic method for storing information. They can support high data densities and can be divided into three general classes. The first are WORM devices that are write once - read many times. The second class is read only. The third class is erasable optical disks. All device classes provide a reasonable method to store information at relatively high data densities in digital formats. There are advances being made in this area and densities will continue to increase. Some classes of optical disks are accepted in some court systems but there is no uniform acceptance of digitally stored information. The main draw-back to these devices is still the medium. The medium is much like a current CD-ROM and is subject to many of the same limitations; for example, optical media will melt at relatively low temperatures.

Limitations of optical storage:

- Fire
- Environmental reactivity
- Requirement for bit stream interpreters
- Not native language
- Media life of about 40 years depending on storage conditions
- Slow data writing
- Not uniformly accepted by the courts

Advantages of optical storage:

- Relativity high data densities
- Relativity rapid reading
- Error correction capabilities
- Not affected by EMP or RF

None of the above methods have been able to match the process developed before the time of the pharaohs for long term storage of information. In those times men chiseled messages in stone as a means of creating enduring records. To be sure, these glyphs have imparted the information of their sculptors for readers millennia later. Some of the important factors that allow the information to be understood millennia later relate to the fact that the information is written in a native language. The Rosetta stone provided the key that allowed to translation of one native language to another. Greek and Latin writing can still be read without the need for a "rosetta stone" because they were written in a still active native language. The new method developed at Los Alamos National Laboratory uses an ion beam to chisel information into durable media. In fact, the durability of the this high-density technique is so great that one observer suggested that "long-term" should be replaced by "geologic," when describing the longevity of this data storage method. The method allows data to be written in native languages, direct human-viewable images, and in binary formats. The information types can be mixed on the same

media. Therefore, it is possible to include in a human-viewable format, instruction on the bit-stream interpreter required to read the binary information.

Limitations of HD-ROM:

- Highest data densities require Scanning Electron Microscope for reading -- SEM are large devices
- Large size of writer

Advantages of HD-ROM:

- Very high data densities 23Gbits - 11,000 Gbits per square inch, higher densities are possible
- Media life of thousands of years
- Not effected by EMP or RF
- Not environmentally reactive depending on material used
- Several reading methods are available
- Native language formats are possible but not required
- Can have mixed densities on the same media
- Can have mixed data formats on the same media
- Rapid reading and writing
- Error correction capabilities
- WORM device (good for archiving information)

The HD-ROM serves two main functions: (1) it stores archival data for very long periods of time, and (2) it stores high-density data in binary, alphanumeric, and graphic formats. Refractive errors from thermal or mechanical shock are unimportant to HD-ROM. Additionally, it is resistant to reversals of magnetic fields that could affect the integrity of the data. This is contrary to the performance of current magnetic storage technologies. All present day data storage media rely on at least one soft, reactive, malleable, or flammable material for data integrity. However, HD- ROM materials are nonflammable, relatively unreactive, hard, and nonmalleable.

Writing Procedure

The high-density data storage is achieved by writing data with a micromill that employs a single focused ion beam. The micromill was built from existing parts, uniquely configured. The process allows writing at the nanoscale level with deep features, thus obtaining a very high data density. Data may be recorded in any vacuum-compatible material. Ion beams can produce high-aspect-ratio (the ratio between depth and width) features with channel widths as small as 75 atoms, or about 5 nanometers and aspect ratios approaching 45. Although these features are extremely small, they are still well under thermal stability limits (that is, the temperature above which atoms rearrange, a

process that results in data loss). Data can be written at a larger scale that would further enhance the survival of the stored information.

The ion beam writing system used for the development of the process is composed of an ultrahigh vacuum system, a load lock, a secondary electron detector, and a liquid metal ion source column. Media are loaded into the load lock chamber and then pumped to a medium vacuum (5×10^{-7} Torr). The media is subsequently transferred to the ultrahigh vacuum chamber (7×10^{-11} Torr, or about one-ten trillionth of an atmosphere). The ion beam then is used to image the physical location of the medium by introducing sufficient secondary electrons to produce a contrast image similar to the more familiar scanning electron microscope (SEM). Subsequently, when operating the ion beam under higher current density, complex milling of digital, graphical or man-readable data is carried out by placing the beam position and dwell time under computer control. The level of control is similar to that available in typical computer aided manufacturing (CAM) software, and the operation in practice is similar to that of a waterjet mill.

The heart of the writer is the ion beam column. A liquid metal (typically gallium) is drawn to the tip of a source under high electric field and is then ionized. Shaping and focusing of the beam is accomplished with well known electrostatic (not magnetic) elements including the apertures, condensers, stigmators, and blanking elements. The resulting current density at the sample surface can be as high as 50 Amps/cm^2 . Features such as channels and holes can be milled at aspect ratios approaching 45 at beam spot sizes near 0.5 microns. Alternatively data can be written at higher areal densities using smaller beam spots and lower currents. The minimum spot size achievable in our current system is about 500 angstroms. Using such a beam, channels as small as 770 angstroms have been reproducibly milled. A practical limit of milled features (channel or dot) size for data storage work appears to be about 5 nanometers (50 angstroms) for archival storage, depending on the materials used.

Since writing done with an ion beam can be controlled, very much like writing done with a dot matrix printer, multiple formats are also possible. Each character is represented by an array of points, each point characterized by a position and dwell time. This means that a feature can represent a binary value, a three-dimensional graphical image or an alphanumeric character. Moreover, different data formats and densities can coexist on the same physical medium.

Currently, the writing capability is limited to the speed of a single ion beam micromill. This allows writing at 276 Gigabyte/day using the higher current densities. To be effective at storing large data bases, advances must take place to allow simultaneous etching (writing) with multiple beams. This is seen as a mechanical issue and plans for a multi-head writer are progressing.

Reading Procedure

One of the unique features of the ion beam writing is that the data can be read in a number of different ways. Scanning electron microscopes provide the capability to read the highest data density while simple laser methods much like current CD-ROMs can be used for the lower density data. The readers are designed so the highest density reader can also read the lowest density information as well. This allows for data migration from low density reader systems to higher densities systems without the need to rewrite the data. Another unique feature is that the media can contain information written at human-viewable low density that describes how the higher density information can be read. The low density information could also contain instructions about any bit-stream interpreters required to make use of the higher density data. This would provide a means to insure that data written today could be read several thousand years from now even with new reader systems and even if the formatting and engineering information related to the media was lost.

There are three basic types of information that the readers must be able to read. The first is binary that is used for the storage of many styles of information such as numeric information, text, and bit map images. The second is one level image and text information in human readable form. The third is multi-level such as gray scale images and 3-D shapes.

Optical Systems

Optical systems fall into two general classes and three basic types of readers. The first class is for low density optical scale information much like current CD-ROMs. This density is a little better than current CD-ROMs and read rates of about 12x. The high density optical reader is designed to push the limits of optical reading efficiency. This density is much greater than current optical systems and read rates approaching 500 Mbytes per second are estimated.

Sub-optical

The sub-optical readers also fall into two main classes. The first is a reading system designed to read sub-optical features without the use of a scanning electron microscope. These readers operate at much higher densities than the high density optical readers discussed above and have read rates in the order of 2 Gbytes per second. The high density sub-optical reader is a modified scanning electron microscope that can read features as small as 3 nm. The read rate for the scanning electron microscope is in the order of 2 to 20 Gbytes per second.

Other reading methods

In addition to the above method, data can be read with atomic force microscopes and STM. At present these methods are slower and more costly.

Applications

Jeff Rothenberg, in the January 1995 *Scientific American*[1], addressed the advantages of digital media for document storage and the need for a long-term solution for preservation of select records. HD-ROM offers such a solution. Of course, some argue there is little data worth storing for such a long period. Others suggest they would prefer a read-write system so that files can easily be updated. These arguments are valid. However, there are a substantial number of files for which read-only, (or read maybe) are appropriate. One example is need for "data assurance" where data must be safe from modifications. As another example, several institutions have an intense interest in maintaining genealogical data. The largest genealogical repository estimates their storage requirements at 12 pentabytes (10^{15}) of digital data. They also have an interest in the storage of genealogical data in a human-viewable form with greater longevity than micro-film. Since the actual storage cost is so low, an estimated \$20.00 per terabyte for media materials, and the storage space so small, it would make sense for many industries and governmental agencies to take advantage of the technology.

As Rothenberg points out, magnetic media, the current choice for digital data storage, are vulnerable to "the ravages of time" through both material degradation and exposure to electromagnetic pulses(EMP). On the other hand, HD ROM is virtually impervious to EMP, and the degree of physical degradation can be controlled by choice of materials. For most circumstances, stainless steel should offer sufficient protection to ensure longevity. The major concern in long-term storage would be to ensure the potential for abrasion was minimized. Given the possibility for atmospheric contamination through increases in acidic content, materials should be protected nominally through prudent encapsulation. No extreme environmental measures such as cryogenic or high vacuum containers would be required.

Numerous recent articles have extolled the virtues of advances in magnetic data storage. Simonds, in *Physics Today*[2], April 1995, suggested recordings are the most significant market for magnetic technology. He states the business sector has mass storage requirements that amount to petabytes of digital data. In predicting advances in magnetic storage density, Simonds states, "10 Gbits/in² would be reached by the year 2005." He further predicts commercial densities of 5 gigabytes/in² and 5 terabytes/in³ by 2003.

These predictions pale when considered against demonstrated current HD-ROM technology. Extant capability for data storage is 23 Gbits/in². Writing done on

high-strength, 10 micron steel tape would produce storage greater than 50 terabytes/in³ even allowing an air space packing factor. If 3 micron tape was used for data storage, then densities in excess of 190 terabytes/in³ are possible. It is believed 3 micron, or thinner, tape would be strong enough for commercial applications. All of these figures are based on current capability. Further, the HD-ROM process does not currently entail any data compression. Many of the present and projected magnetic recording techniques employ data compression to achieve their storage densities. Should HD-ROM employ data compression techniques, then even higher densities than those described are possible.

A recent article by Terry Cook in *Technology Review*[3] discusses the need for better methods of storing information in the computer age. The paper also discusses some common problems associated with storage that do not exist to the human eye.

There are many applications for HD-ROM. Movies offer a substantive example. We are already aware of the substantial number of films that have been lost due to disintegration of materials. An industry is emerging to reconstitute film classics, but this is a time and labor intensive process. While nothing can be done short of this restoration process for degraded films, something can be done to ensure that new films can have long life expectancies. With an estimated 250 Gigabyte/film data requirement for three color separation, each major studio could permanently record a film in less than two days using the multi-head writer.

The National Archives would also be a candidate user. There are many national records, including the Congressional Record, that should be stored for a long duration. Financial institutions would find long-term storage of incorruptible data a major advantage. Then, events such as the stock market information warfare attack depicted in Tom Clancy's recent book, *Debt of Honor*, would have minimum impact. It is the inability to change these records, making retroactive adjustments impossible, that would be of importance to that industry. In fact any business that values a sound data base would appreciate HD-ROM.

This also applies to the scientific community. Large, permanent data bases would be invaluable to researchers doing longitudinal studies. One example, would be NASA's Earth Observation System (EOS) data that is estimated will be collected at a rate of one Terabyte per day. NASA would like to keep the data for 90,000 years. Cross references to such data bases would assure the accuracy of base line data. Deep space probes too could benefit from HD-ROM. Detailed instructions could be etched on very small surfaces. These etchings would be impervious to the extremely harsh environments and unknown electromagnetic fields that might be encountered.

References

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